A Visually Lossless Data Compression Technique for Real-Time Frame/Pushbroom Space Science Imagers

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ABSTRACT

A visually lossless data compression technique is currently being developed for space science applications under the requirement of high-speed push-broom scanning. The technique is also applicable to frame based imaging data. The algorithm first performs a block transform of either a hybrid of modulated lapped transform (MLT) with discrete cosine transform (DCT), or a 2-dimensional MLT. The transform is followed by a bit-plane encoding; this results in an embedded bit string with exact desirable compression rate specified by the user. The approach requires no unique look-up table to maximize its performance and is error-resilient in that error propagation is contained within a few scan lines for push-broom applications. The compression scheme performs well on a suite of test images acquired from spacecraft instruments. Flight qualified hardware implementations are in development; a functional chip set is expected by the end of 2001. The chip set is being designed to compress data in excess of 20 Msamples/sec and support quantization from 2 to 16 bits.

Keywords: Coding, lossy data compression, telemetry images, space science applications, push-broom instruments

1.   INTRODUCTION

Current advances in sensor and detector technology have ushered in a new era of scientific instruments for space applications. Several operational spacecraft science instruments, such as the first NASA Earth Observing Systems TERRA and the French SPOT, either combine unprecedented spatial and signal resolutions or, in addition, offer multi-spectral capabilities. The result is a surge of the data volume that has to be collected, buffered, transported, and archived in the space-to-ground data system.

To alleviate the burden caused by the extra data volume, data compression has been suggested as one of the option to help transport/archive data. Several space missions including NASA s Sub-millimeter Wave Astronomy Satellite (SWAS), Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), Microwave Anisotropic Probe (MAP), Vegetation Canopy Lidar (VCL), Cassini, etc., have implemented lossless compression on space platforms. However, the amount of data reduction achievable with lossless data compression is usually limited by the inherent entropy measurement in the data, and for many remote sensing applications is limited to about two-to-one on average.

For other applications that require higher data reduction, as in quick-look or direct-broadcast of sensor data, a *visually* lossless compression technique is needed. There exist various algorithms that provide good data reconstruction performance at high data reduction, most notably the ongoing International Organization for Standards (ISO) JPEG2000 [1]; however, none has adequately addressed the implementation requirement arising from push-broom instruments. A scan line of data produced by the push-broom type of sensor often exceeds two thousand pixels, only limited amount of onboard buffering and processing time is available before the data has to be transported for direct broadcast through bandwidth constrained channel. In the following paragraphs, the requirements for space application of visually lossless data compression are stated, they are followed by a description of a technique that meets all the requirements, along with its performance on several test images.

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2. REQUIREMENTS FOR SPACE APPLICATIONS

Any implementation of visually lossless or lossy data compression on a space platform has to satisfy several requirements. These requirements were addressed by the Consultative Committee for Space Data Systems (CCSDS) Sub-panel 1A Compression Working Group in 1998. The mandatory flight requirements are:

- Process non-frame based (push broom) as well as frame based input source data.
- Offer adjustable data rate.
- Work with large source quantization ranges up to sixteen bit-per-pixel (bpp).
- Offer real-time processing at or greater than twenty Msamples/sec, and at less than one watt/Msamples/sec. The power consumption includes all buffering and support electronics.
- Require minimum ground interaction during operation.
- Allow packetization for error containment.

The real-time processing requirement in item 4 above is based on currently available radiation hardened circuit fabrication technology. As space science technology advances with time, the quoted processing speed and power consumption need to be adjusted.

3. DESCRIPTION OF THE VISUALLY LOSSLESS COMPRESSION TECHNIQUE

3.1 Overview

The visually lossless compressor consists of several functional modules depicted in Fig. 1. Two main functional blocks are the de-correlator and the bit plane encoder (BPE). The architecture is simple and flexible enough to support various block transforms. The function of the scan converter is to take input imaging data and formats it into square blocks of integer values as input to the de-correlator. The de-correlator can either employ a 2-dimensional discrete cosine transform (2DDCT), a hybrid transform, the Enhanced DCT (EDCT) that performs a size-8 DCT in the Y direction of the imaging data and a size-8 modulated lapped transform (MLT) [2] in the scan direction, or a 2D MLT. The progression from 2DDCT to EDCT, then to 2DMLT, serves to reduce blocking artifact in DCT. The hybrid transform EDCT uses overlapping blocks in the scan line direction to reduce the blocking effect inherent in a 2DDCT, but it allows isolation of strips of eight lines, as is often required by practical implementation in a packet data system. Implementation of 2DMLT will require larger input data buffer but provides better reconstructed image quality. Current system implementation generates 8x8 transform coefficients from the de-correlator.

The bit plane encoder (BPE) first groups the eight-by-eight transform domain components into three family trees; each has one parent, four children, and sixteen grand children. The magnitudes of components are scanned for any most significant bit (MSB) on the scanned bit plane. This bit-plane scanning proceeds from the top-most bit plane downward. The positional information of those identified components is represented by a family tree structure and may be further coded for efficiency. This information along with associated coefficient signs is shifted to the output bit string from higher bit planes to lower bit planes.
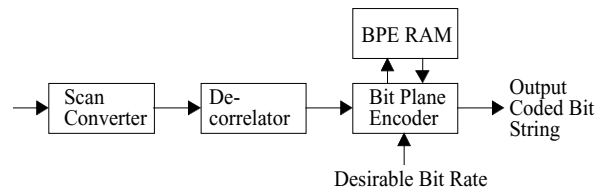

Figure 1. Functional Diagram of the Coder

The BPE random access memory (RAM) holds BPE-processed information for as many input blocks as it can support. The number of input blocks supported by this RAM is identified as one segment of input data. A segment can be as simple as one strip of eight lines, multiples of eight-line strips, or portions of a strip.

The output bit string from the BPE constitutes an embedded data format that allows progressive transmission and decoding to start at a lower bit bpp rate and proceed to a higher bpp rate. The bit string can be terminated at a desirable rate for precise control of output data rate.

3.2 De-correlator

Two transform functions are included: DCT and MLT. The 2D transforms considered within this compression technique are separable transforms that can be executed as two 1D functions applied to the two dimensions in sequence. The specified MLT takes sixteen input data points to provide eight transform components. The input is shifted by eight data samples each time a new MLT is performed.

The MLT is performed with the following equation:

$$X_m[j] = \sqrt{\frac{2}{8}} \sum_{i=0}^{15} x'_m[i] Z_m(i,j)$$

where m is used to index the MLT output block. The j index indicates the jth MLT component in block m. The input data sequence $x[i]$ relates to the data samples in the above equation by:

$$x'_m[i] = x[(m - \frac{1}{2})8 + i]$$

The $Z(i, j)$ function is given by:

$$Z_m(i,j) = -\sin[\frac{\pi}{16}(i + \frac{1}{2})]\cos[\frac{\pi}{8}(j + \frac{1}{2})(i + \frac{9}{2})] \qquad 0 \le i < 16$$

for all blocks except the first and the last. For finite input data, the first and the last MLT blocks are implemented with the boundary conditions in [1].

The DCT is computed by:

$$X[j] = \sum_{0}^{7} x[i] A(i,j)$$

where $A(i, j)$ is:

$$A(i,j) = C_j \sqrt{\frac{2}{8}} \cos[\frac{j\pi}{8}(i + \frac{1}{2})]$$

with $C_j = 1/\sqrt{2}$ when $j=0$ or $C_j = 1$ otherwise.

3.3 Bit Plane Encoder

The frequency components of each block are then scanned from the highest bit plane of their binary representations. At each bit plane nb, the purpose of the scanning is to locate components of magnitude $\ge 2^{nb}$ but $< 2^{nb+1}$ (the lowest bit plane is when $nb = 0$) and transmit their locations in the coded bit string before the information of components at lower bit planes is conveyed. In this coding scheme, quantization is inherently performed by an increase of a power of two as scanning proceeds from higher bit planes to lower bit planes. To facilitate coding, a family tree structure at the nb-th bit plane, shown in Fig. 2, is used to help identify components and guide the component scanning.
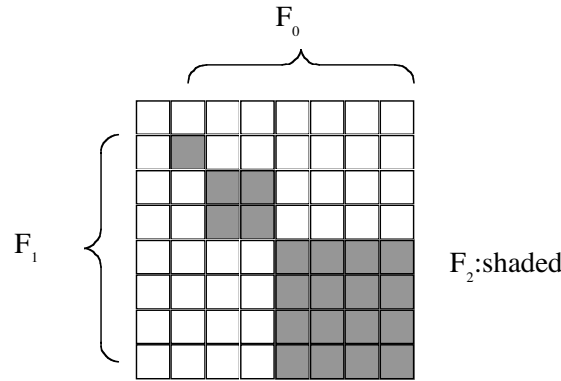
Figure 2. Family Tree Structure on One Bit Plane

3.4 Family Tree Scanning

The tree structure in Fig. 2 consists of three family members: F_0, F_1 and F_2. Each has one parent, four children, and sixteen grandchildren. During tree scanning, these elements are grouped into different types of patterns and each pattern scanned as one entity. Thus parents will be scanned first, followed by the children and the grandchildren. The upper left component represents the DC component and is treated differently.

For each block, the family tree scanning starts at the highest bit plane of all the AC components. At a particular bit plane, *nb,* information extracted from all blocks is concatenated before proceeding to a lower bit plane. This procedure produces an embedded bit stream that starts with information from higher bit planes and proceeds to information from lower bit planes. At the desirable compression bit rate, the bit stream can be stopped for precise rate control.

4. PERFORMANCE

The compression scheme has been tested on different types of imaging data collected on space platforms with excellent results. The image test set consists of both Earth observing and space observing data collected for the Consultative Committee for Space Data Systems (CCSDS) panel 1A compression working group. These images are contributed by the European Space Agency (ESA), the Centre National d Etudes Spatiales (CNES) of France and the NASA of the United States.

The image test set includes 8-bit Earth observing and Mars images, several 10-bit 1km resolution images of various ground coverage (land, ocean, ice, coast line) from the Advanced Very High Resolution Radiometer (AVHRR) onboard National Oceanic and Atmospheric Administration (NOAA) satellite, a few 12-bit solar images collected on ground based telescope, some 12-bit observations from the Hubble Space Telescope (HST) and one 16-bit synthetic aperture radar (SAR) image. This test set presents a wide range of image features from nearly point sources as in star fields, to well defined man made objects such as airport runway and marina. It also contains examples of naturally occurring shapes of various forms as in coastline and ice, and almost random noise within a sunspot or a SAR image. These different image features are visible from a low-resolution representation shown in Fig. 4. The original image size ranges from 512x512 to 2048x2048.

4.1 Quantitative Measurement

Performance test was conducted using three transforms: 2DDCT, EDCT and 2DMLT. A fixed bpp was set for a segment of 8 scanlines. Table 1 provides peak signal-to-noise (PSNR) performance comparison of the three transforms at two moderate bpp s of 1.0 and 0.5 on the test set. The progression from the non-overlapping 2DDCT to overlapping 2DMLT transform results in improvement in PSNR measure for most images except for the wide field planetary camera (wfpc) and faint object camera (foc) images. These two astronomical images collected on HST are examples of sparse features, one contains almost point responses, while the other contains a faintly visible feature. Further study is still needed to determine if coder performance can be optimized on such images.

The performance of the EDCT has been compared with that of JPEG2000 on the same image set by Rountree, et al [3], and is shown to be similar to the JPEG2000 baseline algorithm performance obtained using   precinct of height 8. Other measures such as mean error, mean absolute error, maximum absolute error also have comparable performance to those obtained from JPEG2000.

   The technique has also been compared with current commercially available JPEG (i.e. the   *old* JPEG) algorithm. To simplify simulation, 8-bit image was used for this purpose. JPEG algorithm software was modified to control a desirable data rate for eight scan lines. The modification used adjustment of the quantization values of 2DDCT coefficients for every strip of 8 lines in order to remain close to the desirable rate. The PSNR measurement in Fig. 3(a) shows that Goddard Space Flight Center (GSFC) s 2DMLT technique provides a gain of 1-3 dB for rate between 0.5 — 2 bpp. When both techniques are tested in frame mode, similar performance gain was realized over the old JPEG technique, as shown in Fig. 3(b).

Table 1. PSNR (db) for Different Images at bpp 1.0 and 0.5

Image	size	bits/ pixel	2DDCT bpp 1.0	EDCT bpp 1.0	2DMLT bpp 1.0	2DDCT bpp 0.5	EDCT bpp 0.5	2DMLT bpp 0.5
mars	512x512	8	33.8	34.5	35.0	29.4	29.9	30.5
Spot_panchr	1000x1000	8	37.9	38.2	38.7	34.4	34.6	35.0
Forest(avhrr)	2048x2048	10	48.1	48.4	48.8	42.5	42.8	43.3
Ice(avhrr)	2048x2048	10	45.8	46.3	46.7	41.3	41.8	42.2
India(avhrr)	2048x2048	10	42.5	43.0	43.3	37.5	37.9	38.4
Ocean(avhrr)	2048x2048	10	43.5	43.8	44.0	38.8	39.2	39.5
solar	1024x1024	12	48.6	49.0	49.4	44.4	44.7	45.2
Sunspot	512x512	12	54.2	54.6	55.0	50.2	50.9	51.6
Wfpc(hst)	800x800	12	68.4	67.8	66.3	66.2	64.5	60.1
Foc(hst)	1024x512	12	67.1	66.8	66.4	64.4	64.2	62.1
SAR	512x512	16	53.0	53.1	53.2	49.9	49.7	49.5
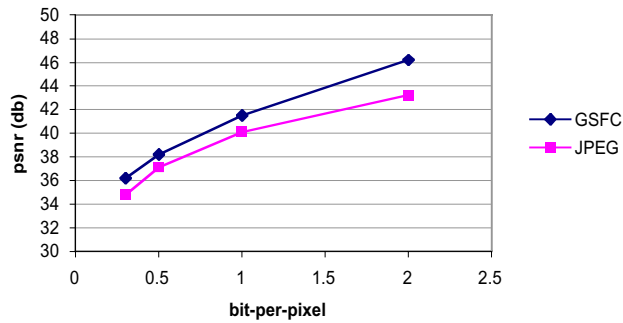
Fig. 3(a) Strip Mode Performance
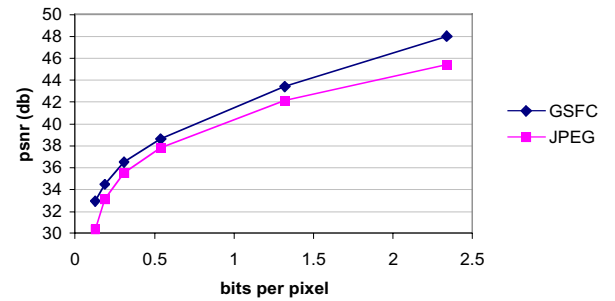
Fig. 3(b) Frame Mode Performance

4.2 Visual Evaluation

   Quantitative evaluation using measures of PSNR and others provides a first indication of the performance of a compression technique. Algorithms which have similar quantitative performance are usually rated as such. However, visual evaluation may or may not provide consistent results. Visual inspection of decompressed images can identify if features have been deformed or artifact has been added as a result of compression processing. As an example, visual evaluation is performed on two sub-images from the high resolution 8-bit data in Fig. 4(b). The sub-images are magnified to provide details of features.

In Fig. 5 and 6, sub-image marina compressed by different techniques at 1.0 and 0.5 bpp is visually evaluated. Similarly in Fig. 7 and 8, sub-image airport is evaluated. It is apparent that at both 0.5 and 1.0 bpp the non-overlapping transform 2DDCT results in blocking effect at 8x8 block boundary, and the semi-overlapping EDCT contains banding which is the blocking effect in y-dimension. The overlapping 2DMLT reduces the blocking significantly. For comparison, a JPEG2000 frame-processed image is included [4]. This frame-processed image has a PSNR over 0.5 db better than the strip-processed 2DMLT image, yet the visual quality is comparable to the 2DMLT results with slightly higher level of blurring over high contrast details.

4.3 Error Containment

One of the concerns in using data compression in space environment is the possibility of bit errors in the communication link. Current recommendation from CCSDS is to use a packet data structure which supports error correction scheme [5]. Error propagation in decompression as a result of un-corrected bit error should be limited to confined data source. The problem can become severe for push-broom instrument which generates data in a continous fashion without frame boundary. To reduce encoder and decoder complexity, the compression technique developed here will not employ additional error protection scheme beyond what is being provided by the CCSDS data architecture. Therefore when 2DDCT or EDCT is used, the error propagation will be limited to the 8 scan lines (or portion of) that are required for the 8x8 transform. When 2DMLT is used, analysis and simulation shows that only up to 16 scan lines (or portion of) will be affected in a worse case scenario for push-broom applications.

5.   TECHNOLOGY STATUS

Radiation hardened implementation of the compression scheme is being pursued. Currently, a custom VLSI chip for performing EDCT and the 2D DCT has been designed and fabricated. Its processing speed exceeds 35 Msamples/sec and it can process from 2 to 16 bits/sample. Based on the experience gained, an implementation of the 2DMLT is currently being planned. The VLSI architecture for BPE is completed and a specification has been defined. A functional chip is expected in 2001. The compression scheme is simulated in software and has been tested on various types of space data including NOAA/LRPT and MOLS/DMSP with satisfactory results.

6. CONCULSION

A high performance   lossy data compression scheme has been developed for space applications using radiation tolerant technology. This scheme offers real-time (over twenty Msamples/sec) processing on push-broom types of instruments. The technique produces an embedded bit string with the desirable features of precise rate control and no operator intervention.

7.   ACKNOWLEGEMENT

The authors wish to thank Gilles   Moury of CNES for permission to use Figs. 5(f), 6(f), 7(f) and 8(f) for comparison of results.

8.   REFERENCES

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3.   J. Rountree. T. Flohr and M. Marcellin: The Scan-Based Processing Mode in JPEG2000 , presented in May 15, 2000 CCSDS P1A meeting.
4.   Gilles Moury, Visual Evaluation of CCSDS Candidate Algorithms , presented in May 15, 2000 CCSDS P1A meeting.
5.   Consultative Committee for Space Data Systems, *Advanced Orbiting Systems, Networks and Data Links: architectural specification,* CCSDS 701.0-B-2 Blue Book, 1992.
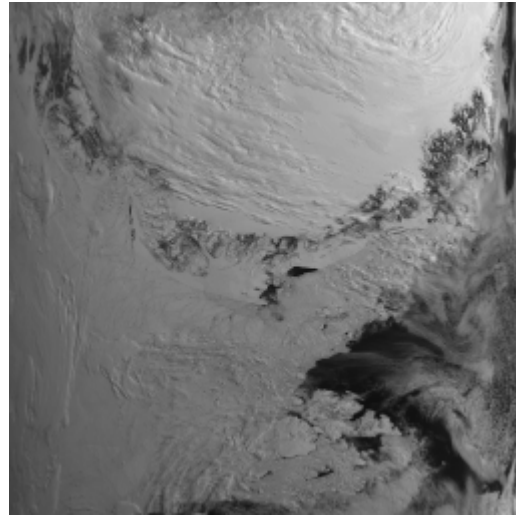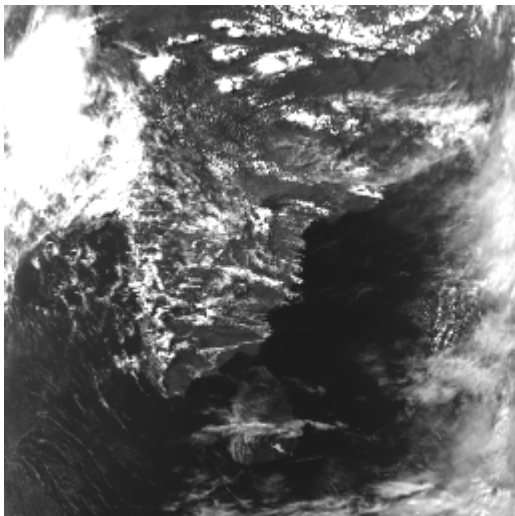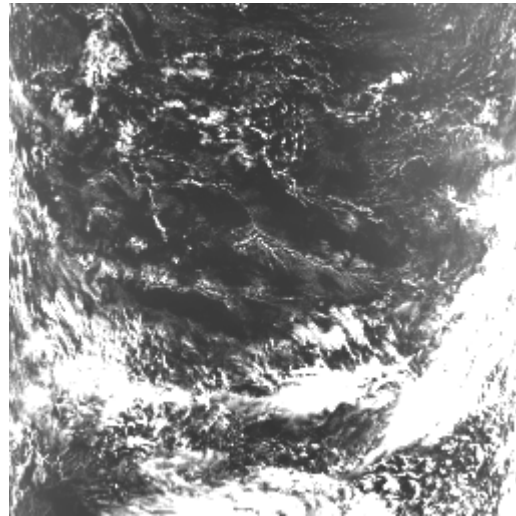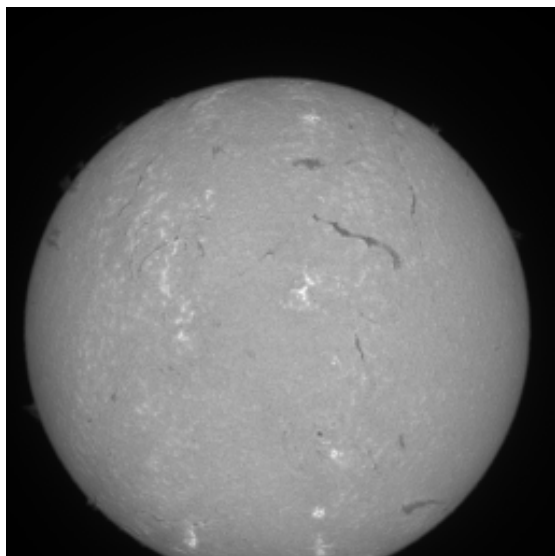
a. Mars surface

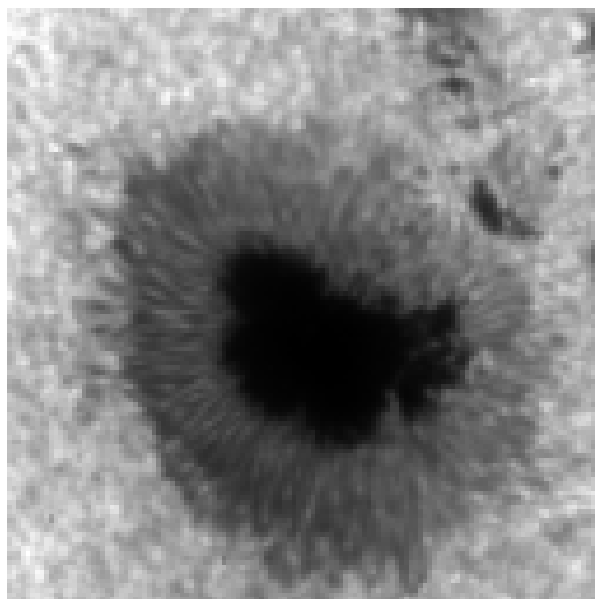b. Spot Earth View
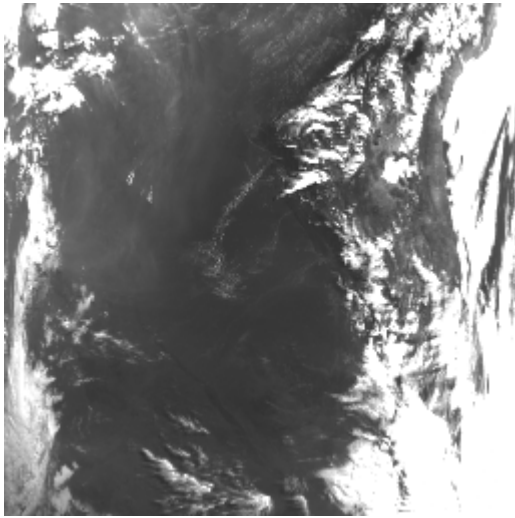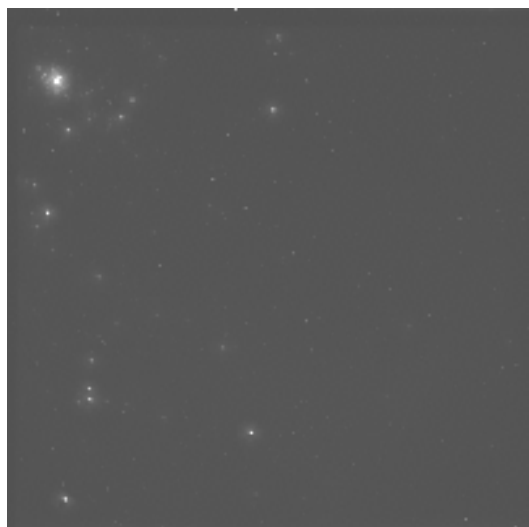

c. Forest land

d. Ice

e. India

f. Ocean
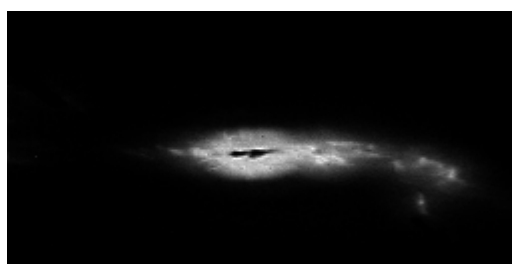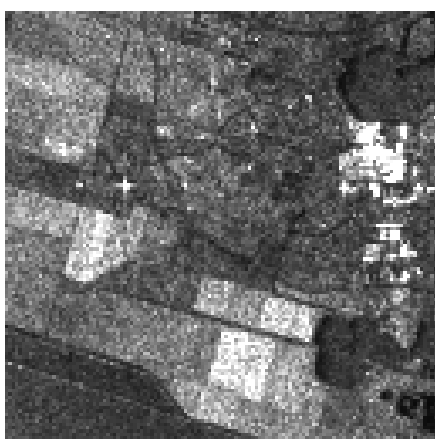
Fig 4. Test Images

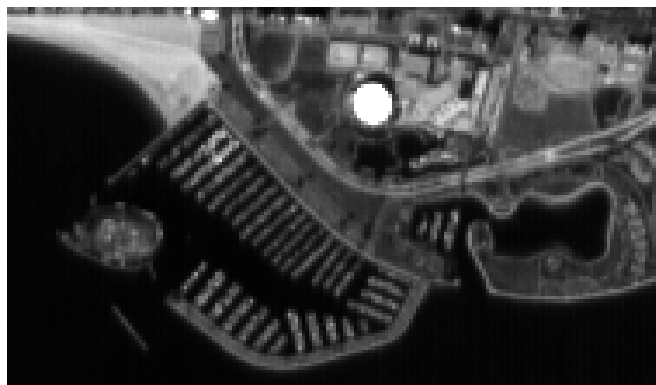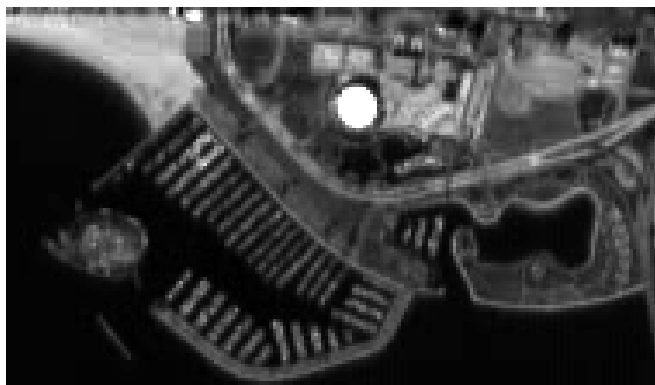g. Solar Image

h. Sun Spot

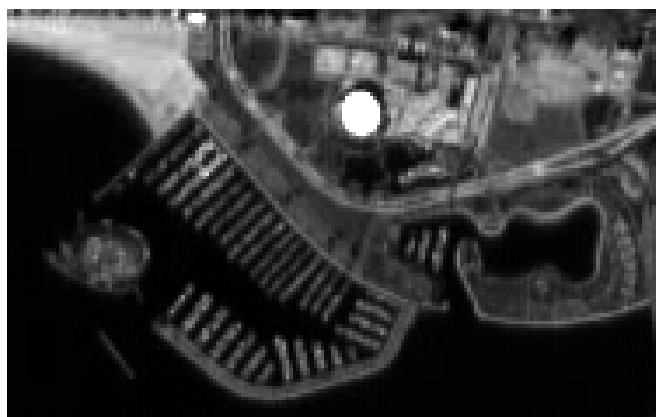i.wfpc Star Field

j. Galaxy from foc
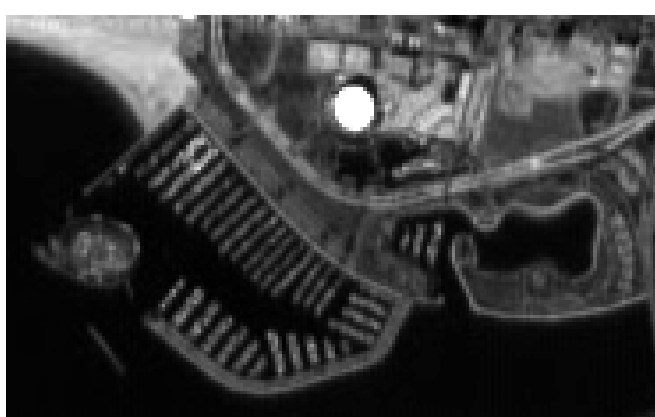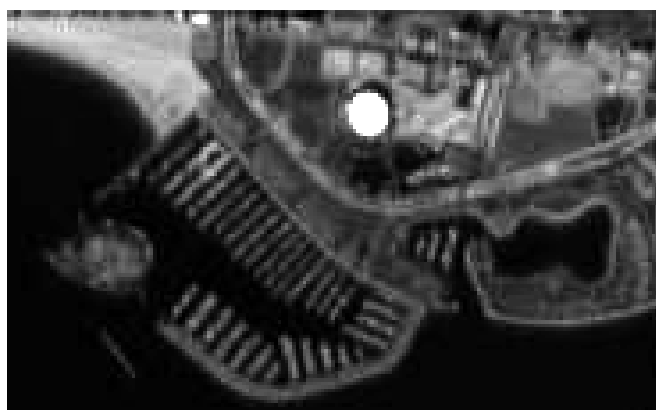

k. SAR Image

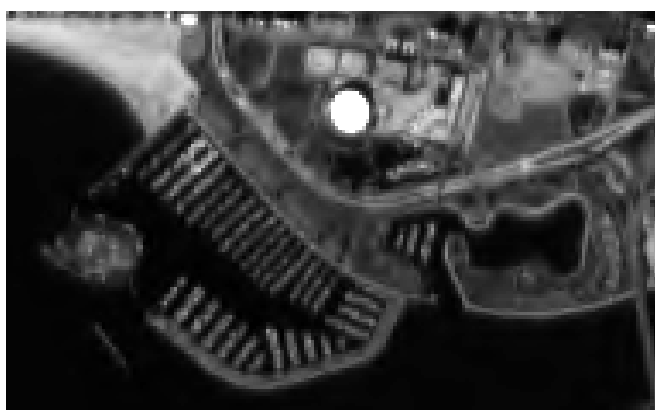Fig. 4 Test Images (Cont d)

a. Original
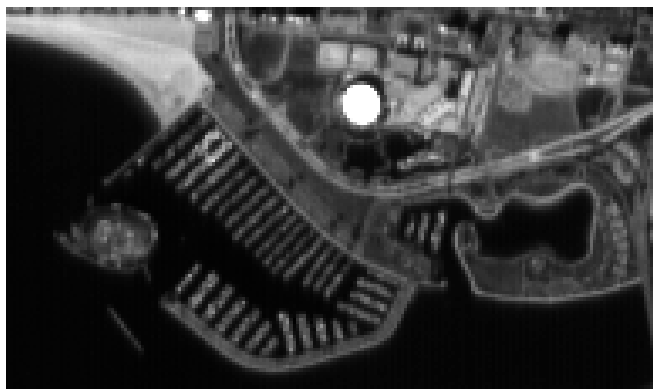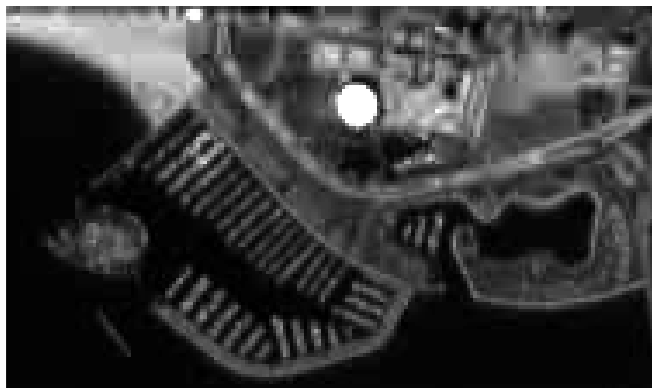
b. 2DDCT+BPE

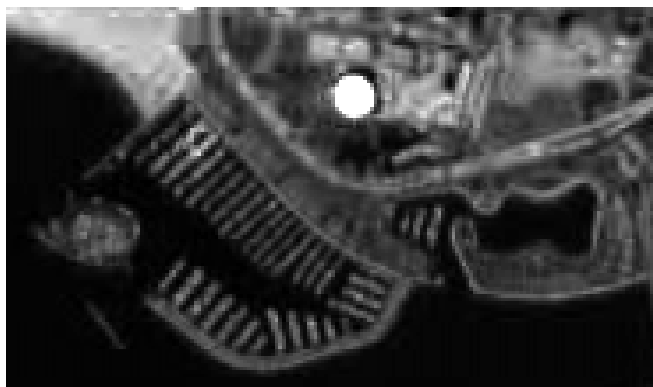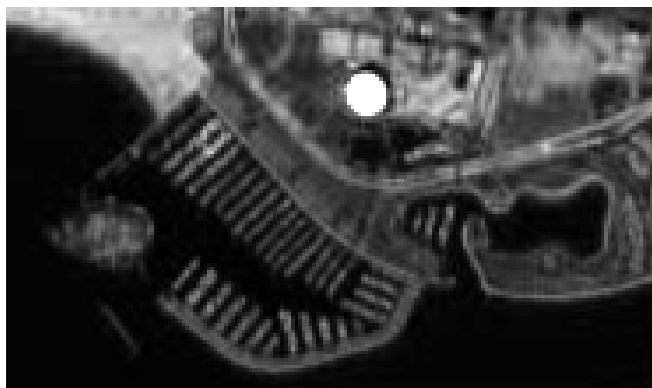c. EDCT

d. 2DMLT+BPE

e. JPEG

f. JPEG2000

Fig. 5 Marina at bpp 1.0

a. Original

b. 2DDCT+BPE
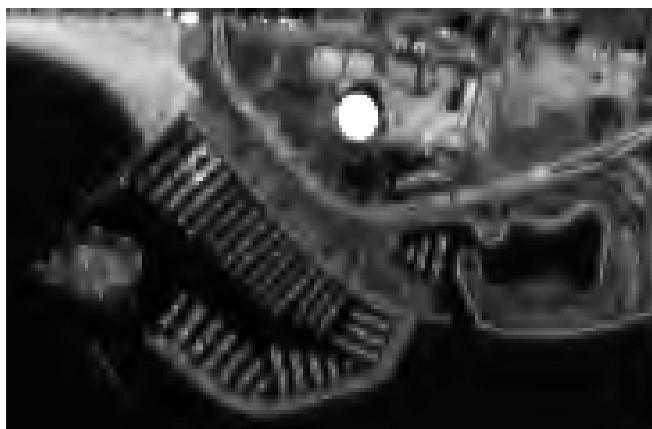
c EDCT+BPE

d. 2DMLT+BPE

e. JPEG

f. JPEG2000

Fig. 6 Marina at bpp 0.5

a. Original
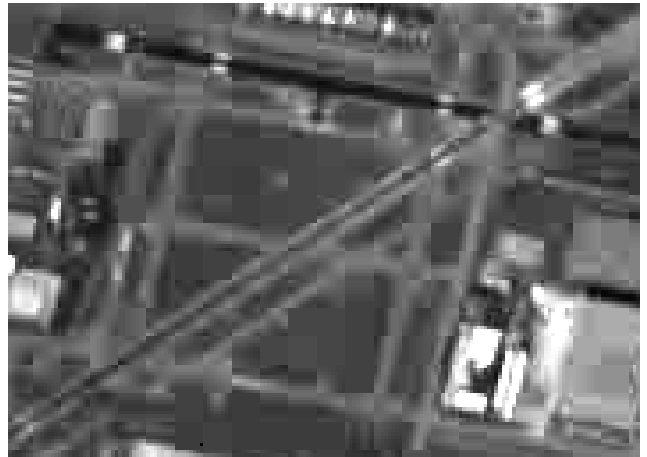
b. 2DDCT+BPE

c. EDCT+BPE

d. 2DMLT+BPE

e. JPEG

f. JPEG2000

Fig. 7 airport at bpp 1.0

a. Original

b. 2DDCT + BPE

c . EDCT+ BPE

d. 2DMLT + BPE

e. JPEG

f. JPEG2000

Fig. 8 airport at bpp 0.5